Conventional Neutrino Beams: State-of-the-Art & Prospects

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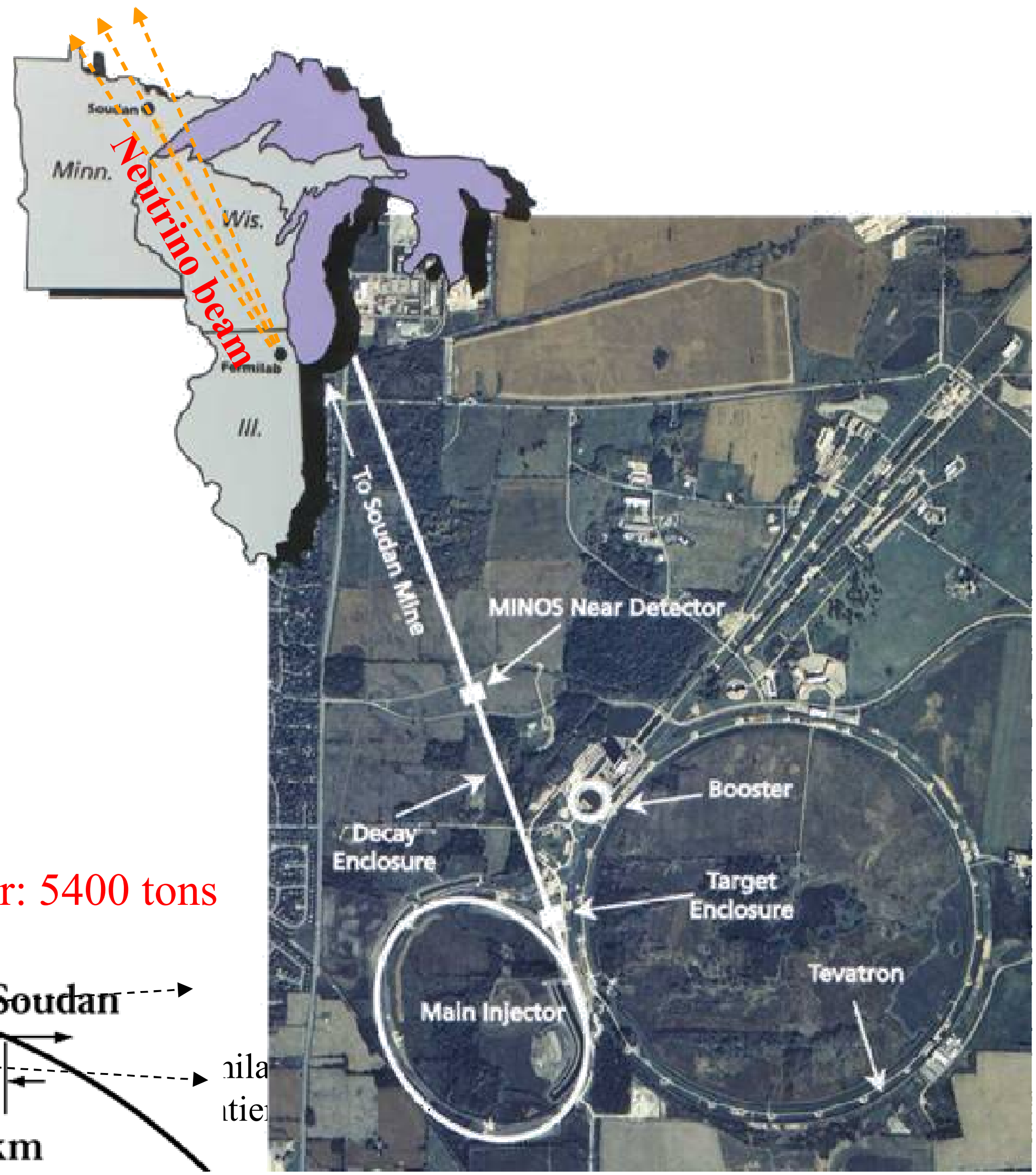
Outline

- Elements of a Conventional Beam
  - NuMI as an example
- Design Status of LBNE
- Challenges to Conventional Beams

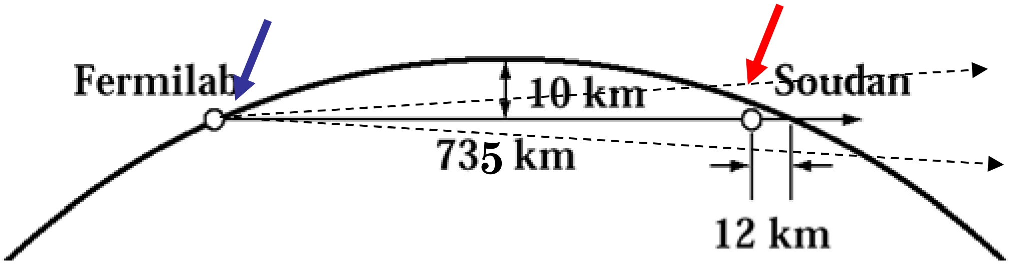
The NuMI Facility

- High-power neutrino beam for oscillation experiments
  - ➢ Beam tilted 3.3° down into the earth
- Neutrino beam travels to northern Minnesota
  - ➢ 735 km baseline
  - ➢ Intense source at Fermilab
  - ➢ Oscillated source in Minnesota
- Commissioned in 2004
- Operating since 2005



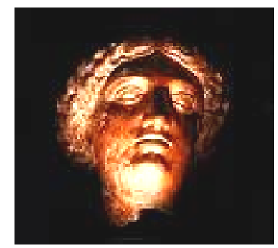
Near Detector: 980 tons

Far Detector: 5400 tons



Users

- MINOS – Main Injector Neutrino Oscillation Search
  - Initial user – built concurrently with NuMI
  - Muon-neutrino disappearance search
- MINERvA experiment in operation
  - Sited in MINOS Fermilab hall
  - Extensive portfolio of high-statistics measurements



- NOvA experiment in construction
  - New detector in northern Minnesota
  - Includes beam upgrades to 700 kW
  - Electron-neutrino appearance search

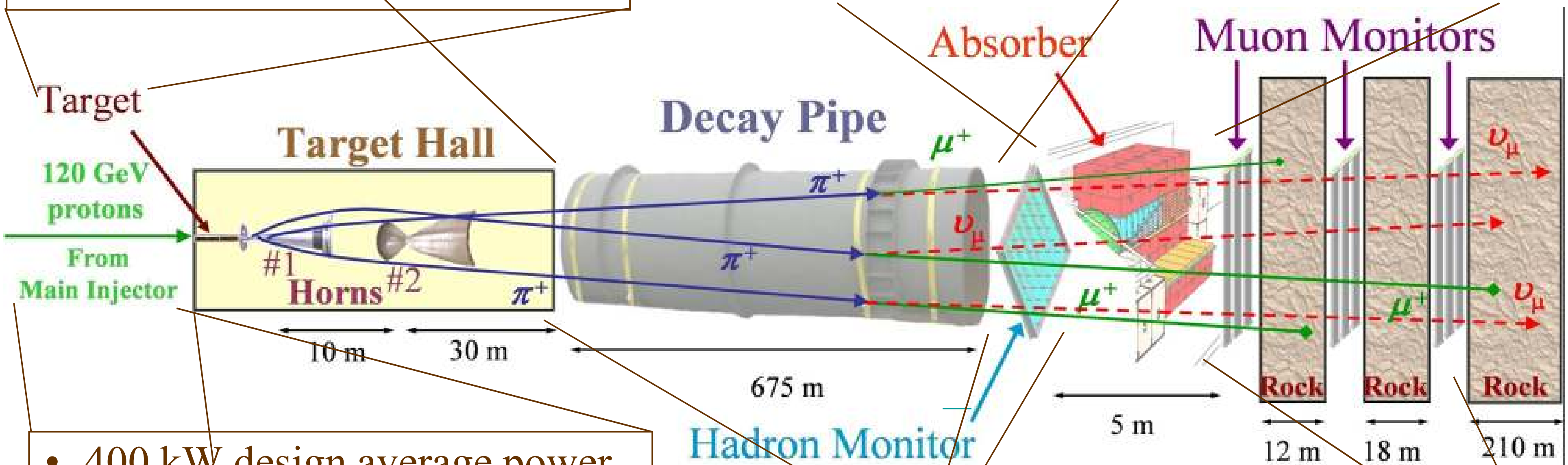
The NuMI Beam

"Neutrinos at the Main Injector"

- Absorbs ~ 40 % of beam power
- Allows high-energy muons to penetrate

- 2 m diameter
- Roughly decay length for 10 GeV π^+
- He-filled

- 2 interaction length, C target
- Produces π^+, K^+ mesons



- 400 kW design average power
- 700 kW upgrade for NOvA
- $\sigma \sim 1$ mm

- Pulsed focusing horns
- Toroidal magnetic field
- Parabolic inner conductor profile
- Focuses meson momentum band

- Measure hadron & muon fluxes
- Arrays measure distributions

NOvA - NuMI Upgrades

- Target Replacement
  - New design for 700 kW
  - External to horn
- Target Hall Re-arrangement
  - Higher Energy
- Various shielding and magnet reconfigurations

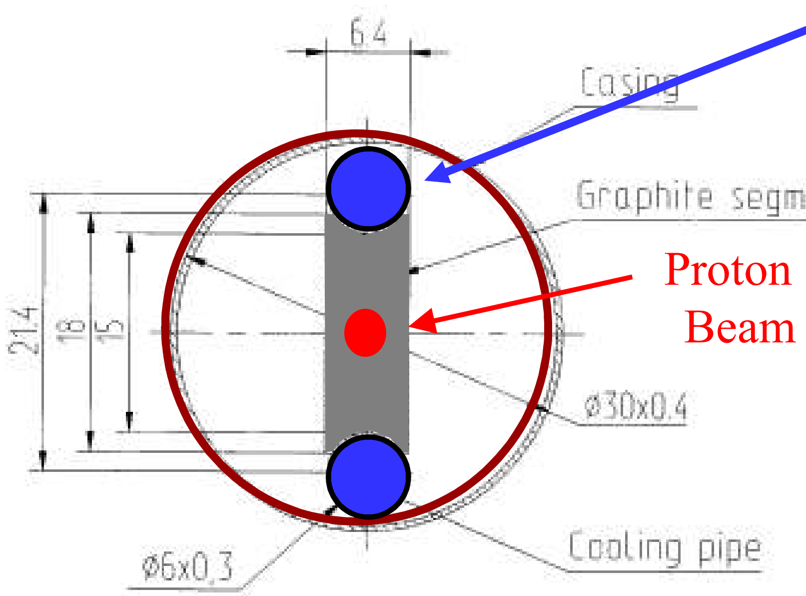
MINOS / NOVA / LBNE Targets

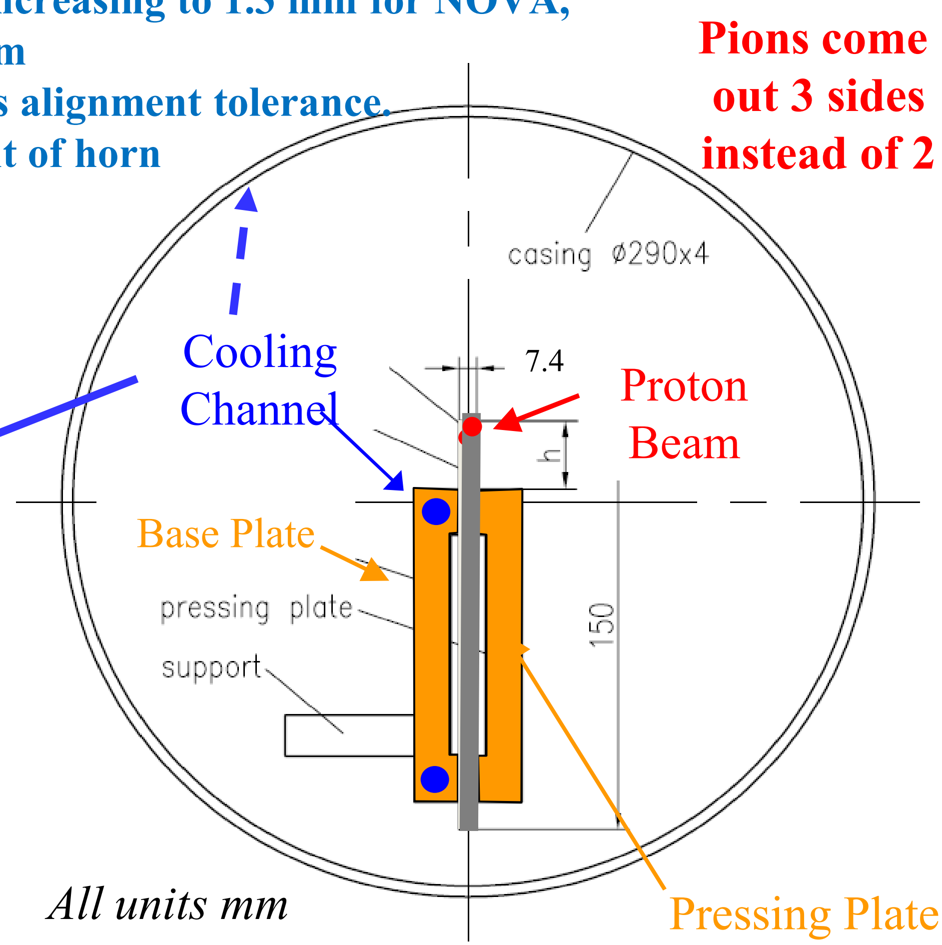
	NUMI / MINOS	NUMI / NOVA	LBNE
Distance to far detector	735 km	810 km	1300 km
Desired n energy	1 to 15 GeV	2 GeV	0.8 & 2.7 GeV
Detector Off-beam-axis angle	0	14 mrad	0
Design beam power	400 kW	700 kW	700 kW initial
Energy per proton	120 GeV	120 GeV	120 GeV
Number of horns	2	2	2
Target length	0.95 m	1.2 m	1 m
Distance between target downstream end and horn	1.6 m to -0.6 m (Variable)	0.2 m (Not in horn)	-0.95 m (In horn)
Protons/spill	4.4 E13 max.	4.9 E13	4.9 E13
Repetition rate	2.2 sec	1.33 sec	1.33 sec

MINOS & NOvA Target Comparisons

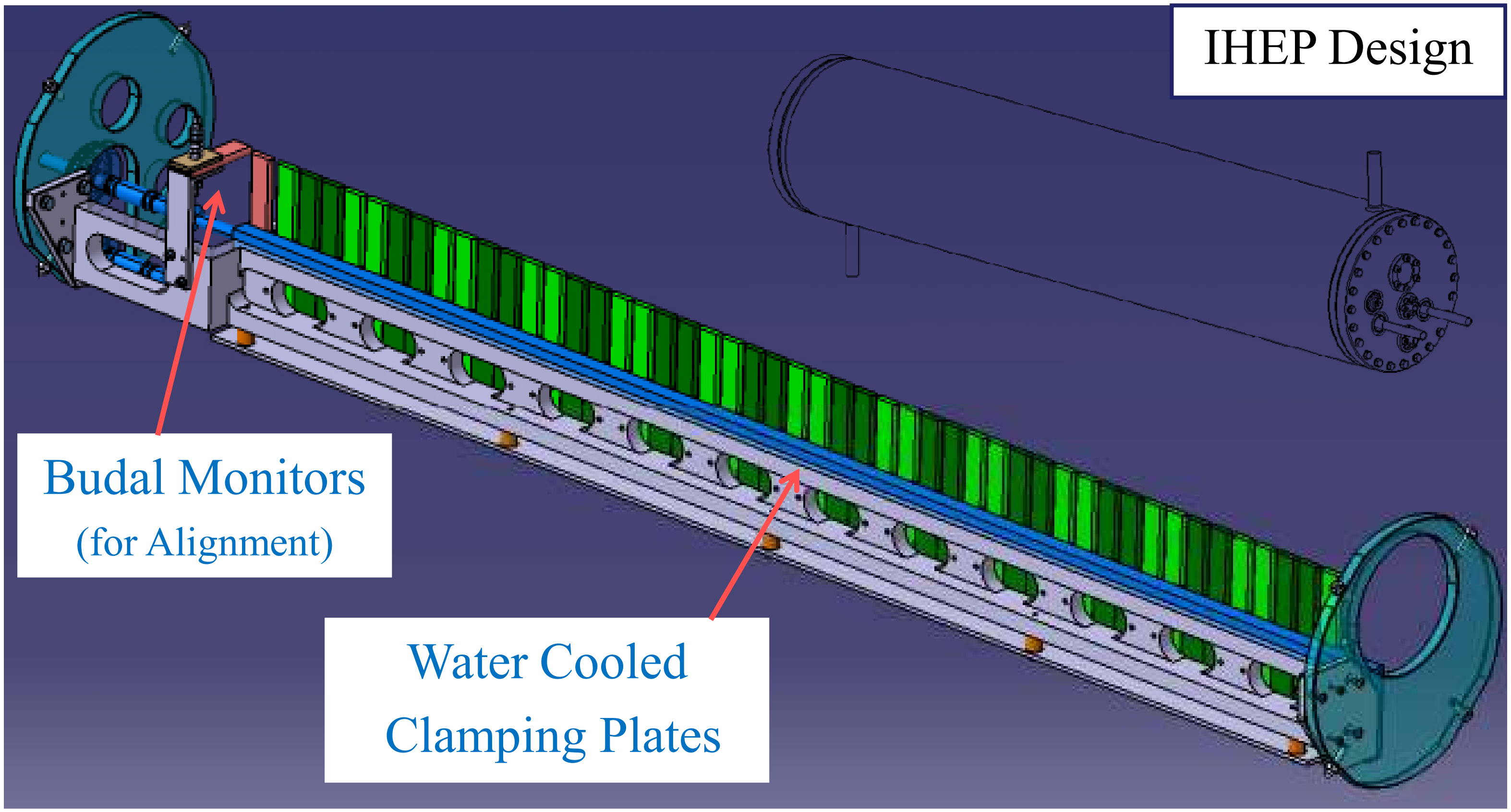
MINOS beam spot size of 1.1 mm RMS is increasing to 1.3 mm for NOVA, increasing 6.4 mm target width to ~ 7.4 mm
- reduces the neutrino flux ~ 1%, but eases alignment tolerance.
NOvA target cooling simplified by being out of horn

Spacing between fins
0.5 mm / 24 mm versus 0.2 mm / 20 mm





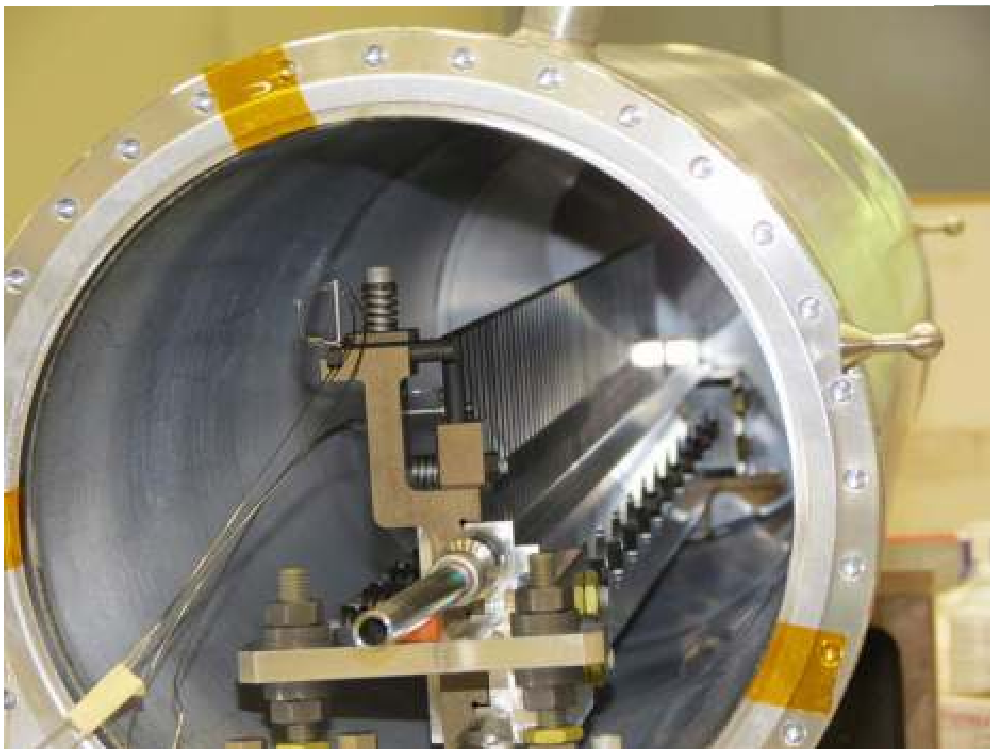
NOVA Target



Nominal max. beam power 700 kW

NOvA Target Production

- Proceeding with two construction paths:
  - 1st target built @ RAL
  - One each under construction at RAL & Fermilab
- Hope to have a target lifetime of ~ 1 year

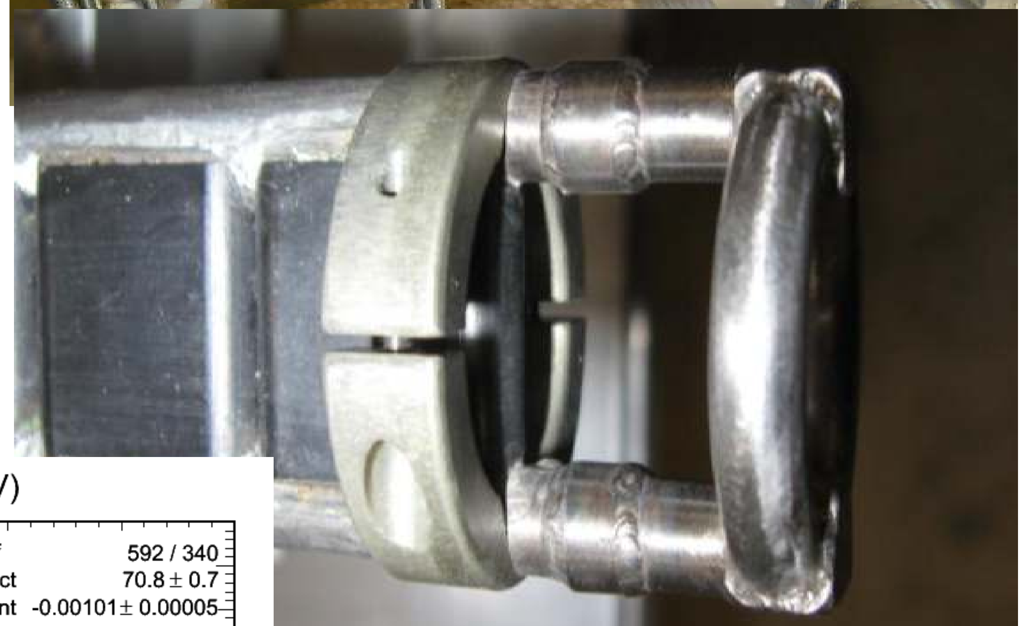


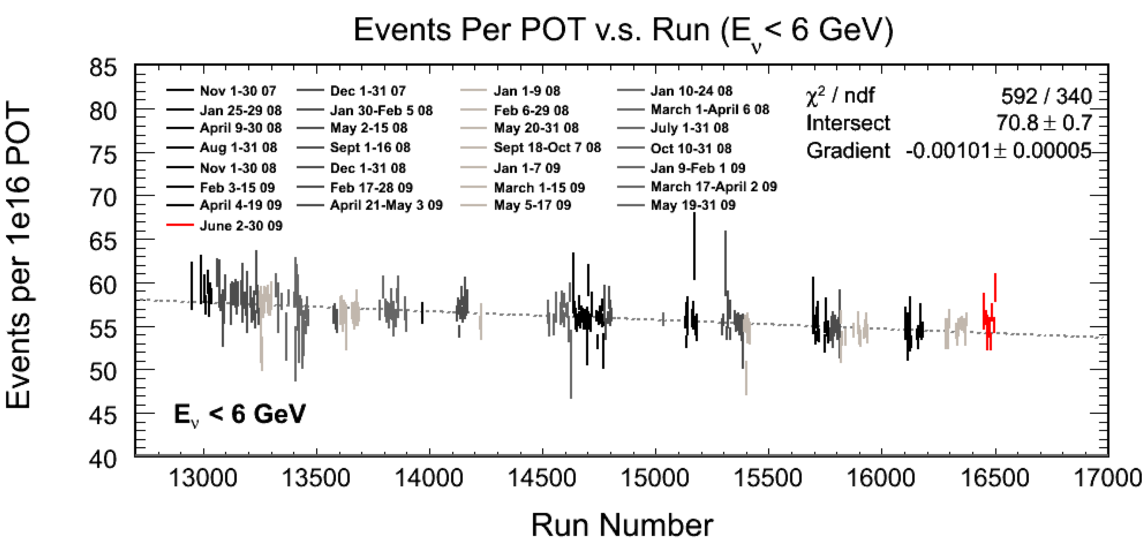
Experience with MINOS targets

	Max. Proton/pulse	Max. Beam Power	Integrated Protons on Target
Target Design specification	4.0e13 p.p.p. at 120 GeV	400 kW	3.7 e20 p.o.t. or 1yr minimum lifetime
NT-01	3.0 e13	270 kW	1.6 e20
NT-02	4.0 e13	340 kW	6.1 e20
NT-03	4.4 e13	375 kW	3.1 e20
NT-04	4.3 e13	375 kW	0.2 e20
NT-05	4.0 e13	337 kW	1.3 e20
NT-06	3.5 e13	305 kW	0.2 e20
NT-01 rerun	2.6 e13	228 kW	0.2 e20
NT-02 rerun	3.8 e13	330 kW	0.4 e20
NT-07	4.0 e13	345 kW	2.5e20

Target Issues

- Predominant failure mode was cooling
  - ➢ Also an issue for horns
  - ➢ Many lessons were learned in design and in quality control
- NOvA target is more robust in its design
  - ➢ Made possible by being outside of the horn.
- Graphite degradation was observed on one target
  - ➢ May ultimately limit the performance of the material



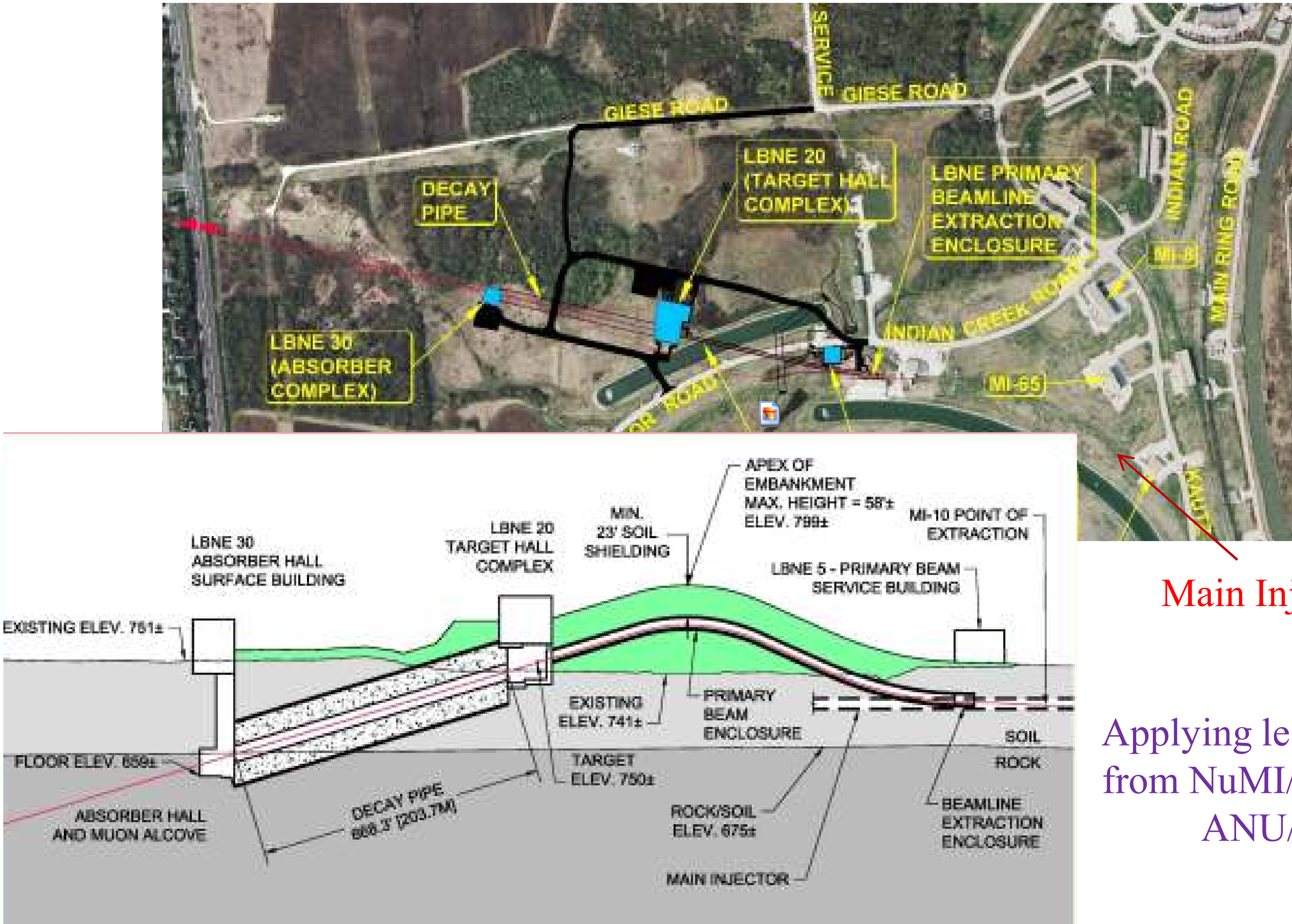


pability

NuMI Summary

- Has now operated 7 years
  - Satisfies multiple users
  - Plan 8+ years of operation for NOvA
- Operated up to 400 kW, 700 kW planned for NOvA
- Major issues when running
  - Cooling of targets & horns
  - Corrosion
  - Radionuclide production

LBNE Beamline Reference Design

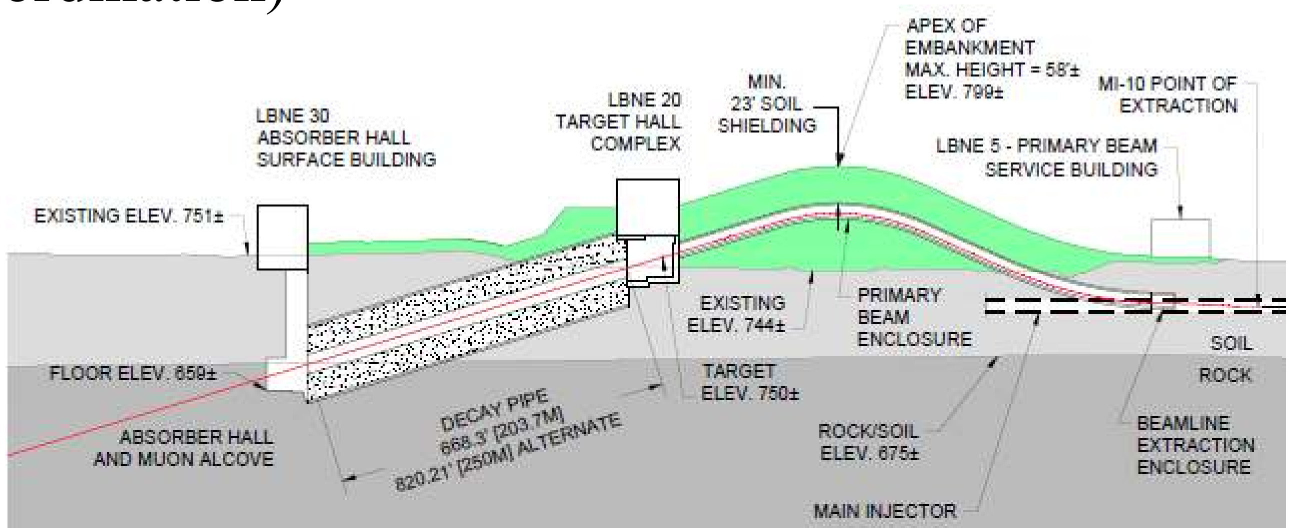


Main Injector

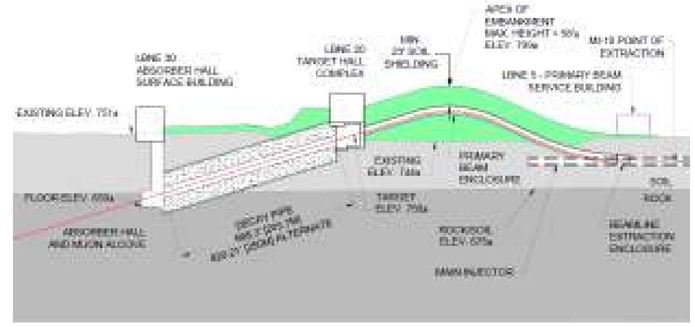
Applying lessons learned from NuMI/MINOS and ANU/NOvA

Beamline

- Primary Beam (magnets, magnet power supplies, LCW, vacuum, beam instrumentation, beam optics and beam loss calculations)
- Neutrino Beam (primary beam window, baffle, target, 2 focusing horns, horn power supplies, target pile, decay pipe, absorber, RAW, tritium mitigation, remote handling, modeling, storage of radioactive components)
- System Integration (controls, interlocks, alignment, installation infrastructure and coordination)
- Providing specs for Conventional facilities (hall sizes, decay pipe size, shielding thicknesses, etc.)



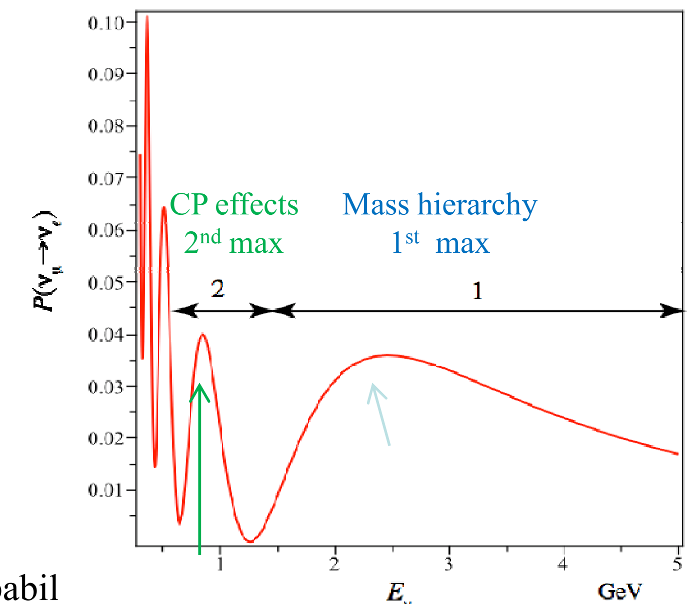
Beamline Configuration



- The target hall is above grade (reduced humidity)
  - Easier construction of conventional facilities and installation of components
  - Accessible near grade, easier to address possible radiological issues.
- 5.5 m thick concrete shielding around the decay pipe
- Water inflow fluctuations are not a major risk
- Geomembrane barrier system ensures that water only leaves facility in a controlled way

Beamline Requirements & Assumptions

- The driving physics considerations for the LBNE Beamline are the long baseline neutrino oscillation analyses.
- Wide band, sign selected beam to cover the 1st and 2nd oscillation maxima. Optimizing for E_ν in the range 0.5 – 5.0 GeV.
- The primary beam designed to transport high intensity protons in the energy range of 60-120 GeV to the LBNE target (focusing on 120 GeV).
- Start with a 708 kW beam (ANU/NOvA at 120 GeV), and then be prepared to take profit of the significantly increased beam power (~2.3 MW) available with Project X allowing for an upgradability of the facility.



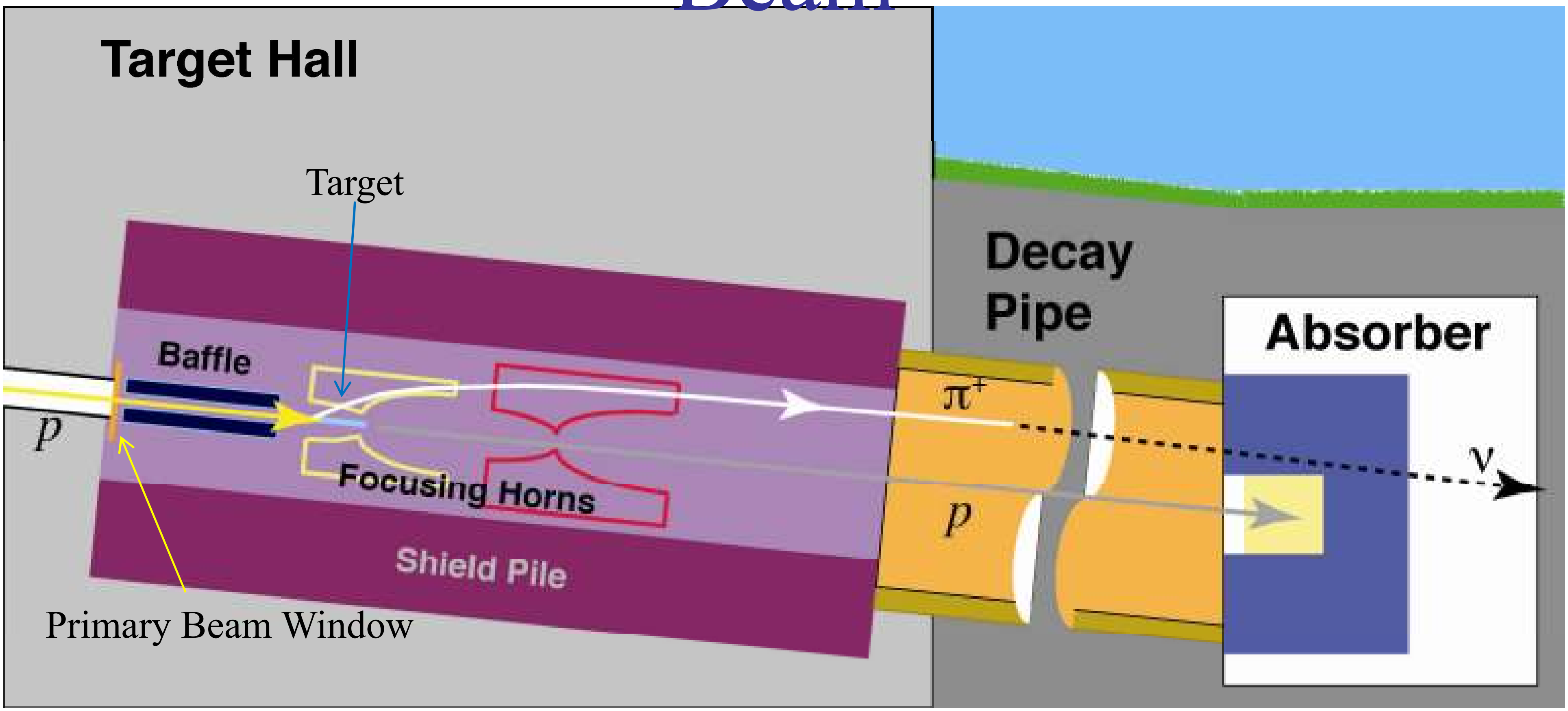
Primary Beam

- The LBNE Primary Beam will transport protons of 60 - 120 GeV from the MI-10 extraction point of the Main Injector (MI) to the target in the LBNE Target Hall to create a neutrino beam. The fractional beam loss design goal is 5E-7 for 708 kW operation.
- The primary beam elements necessary for transport include vacuum pipes, dipole, quadrupole and corrector magnets and beam monitoring equipment (BPMs, BLMs, Beam Profile Monitors, etc.).

The beam lattice design will have ~80 conventional magnets:

Magnet	Common Name	Steel Length	Nom. Strength at 120 GeV	Count
RKB Kicker	NOvA extraction	~1.720 m	0.0237 T	5
ILA	MI Lambertson	2.800 m	0.532 / 1.000 T	3
ICA	MI C Magnet	3.353 m	1.003 T	1
IDA/IDB	MI Dipole 6 m	6.100 m	1.003 - 1.604 T	13
IDC/IDD	MI Dipole 4 m	4.067 m	1.003 - 1.604 T	12
QQB	3Q120 quadrupole	3.048 m	9.189 - 16.546 T/m	17
QQC	3Q60 quadrupole	1.524 m	11.135 - 17.082 T/m	4
IDS	LBNE trim dipoles	0.305 m	Up to 0.365 T	23

Major Components of the Neutrino Beam

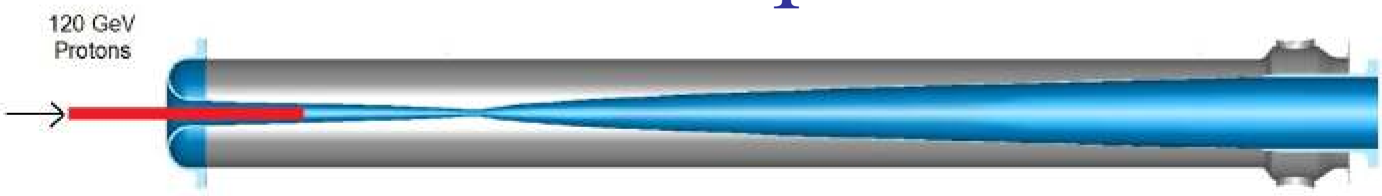


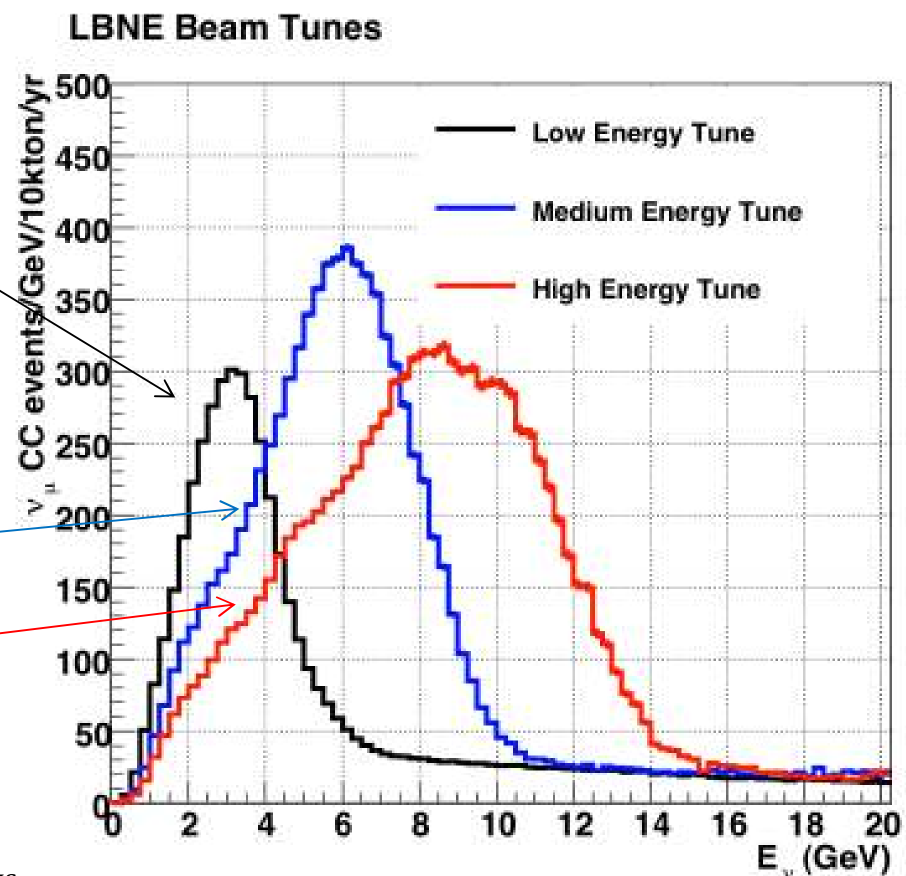
NuMI design Horns.

NuMI-like low energy target for 708 kW operation.

Target inserted into Horn 1.
Upstream end of target at -35 cm relative to the upstream face of Horn 1.
Tunable neutrino energy spectrum.

LBNE Beam Tunes: Moving the target with respect to Horn 1

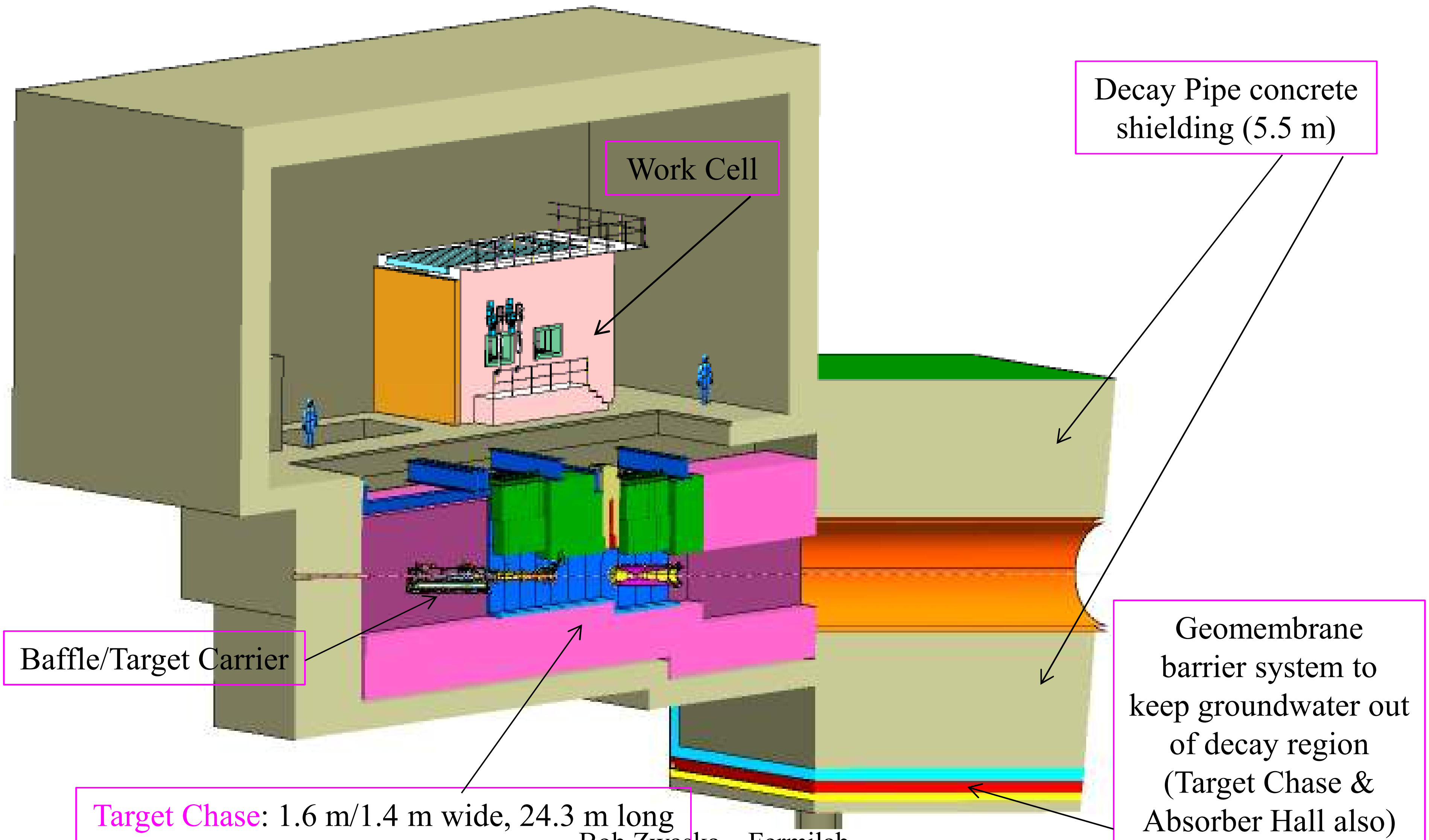




Move target 1.5 m upstream of Horn 1

Move target 2.5 m upstream of Horn 1

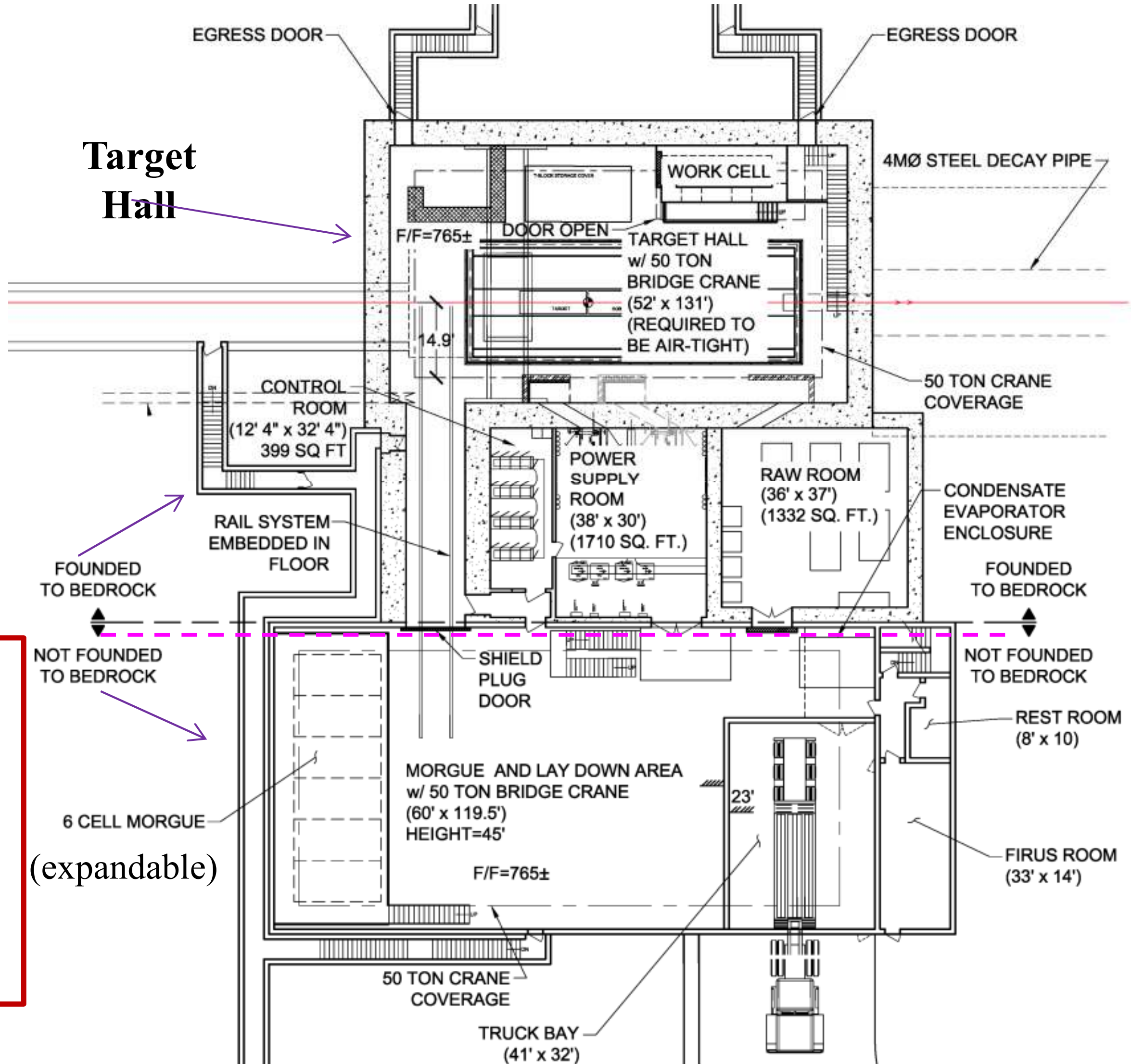
Target Hall/Decay Pipe Layout



Target Hall Complex

3 story structure
Gross floor area
22,200 SF

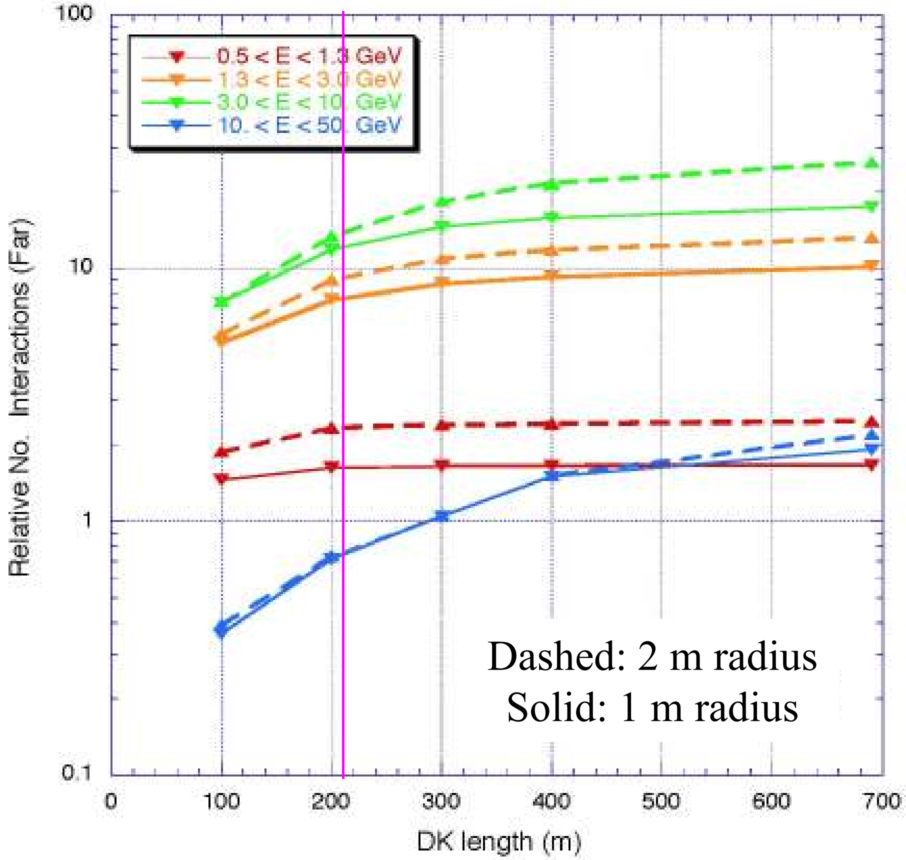
Target Hall



6-cell radioactive component storage morgue has sufficient space for 2 years of operation at 708 kW. Fermilab assumed to provide any additional storage needed

Decay Pipe Considerations and Reference Design

Far Detector Neutrino Interactions vs Decay Pipe Length



- Dimensions: Radius of 2m.

Length of 203.7 meters.

Real estate allows for up to 250 m.

- Filling-Cooling: Air – filled and

air-cooled decay pipe is the default.

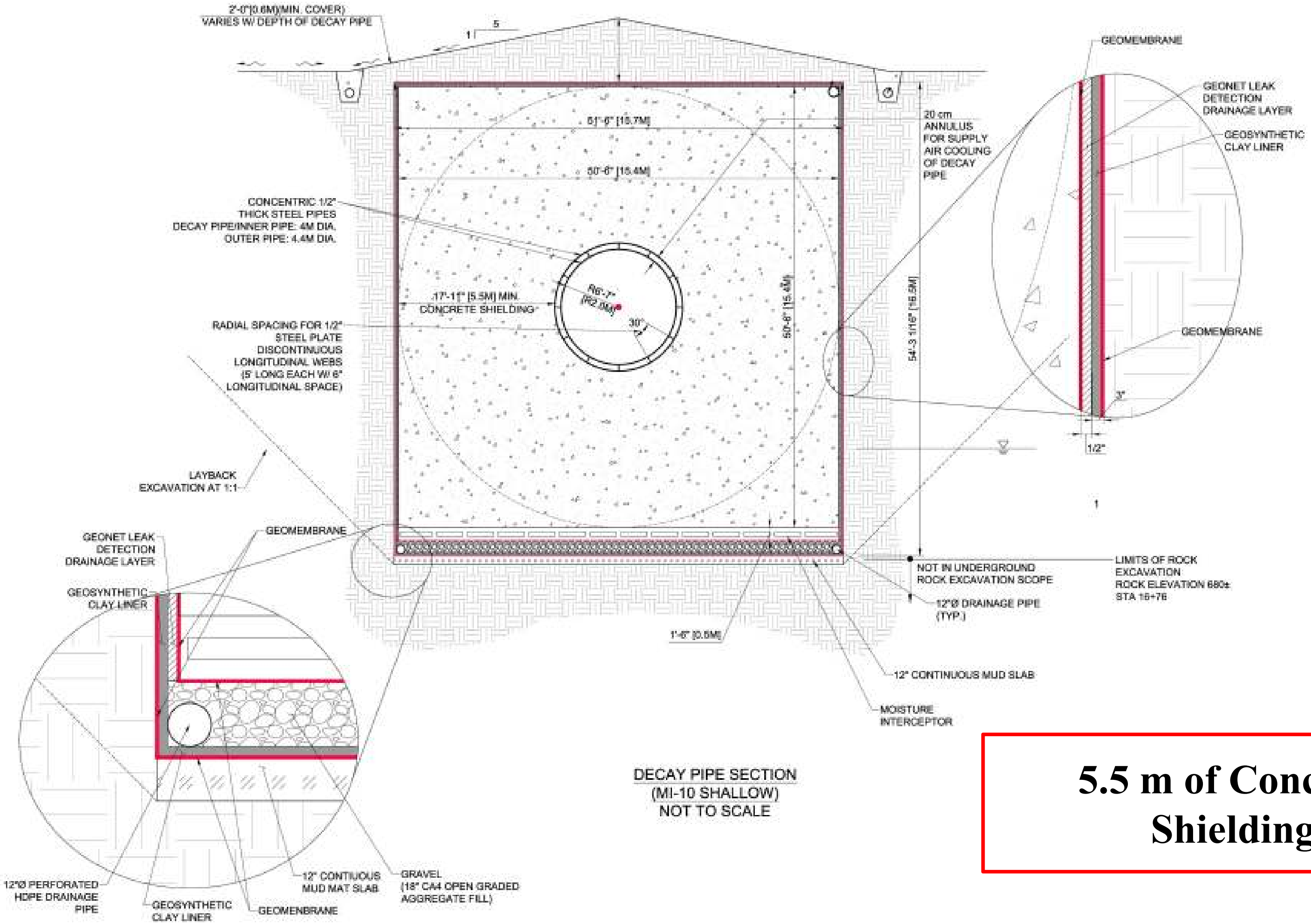
Helium-filled pipe which is air OR water cooled and sealed-off from the target hall is an alternative.

- ➢ A substantial part of the decay region is in soil with limited rock excavation required.

Shielding: 5.5 m of concrete

Decay Pipe configuration

water barrier/intercept system

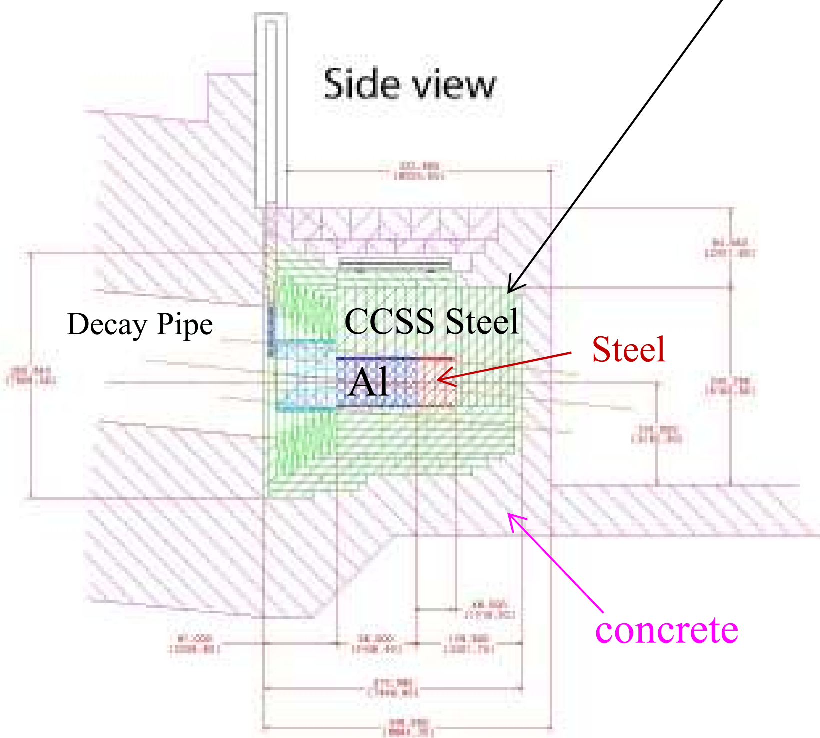


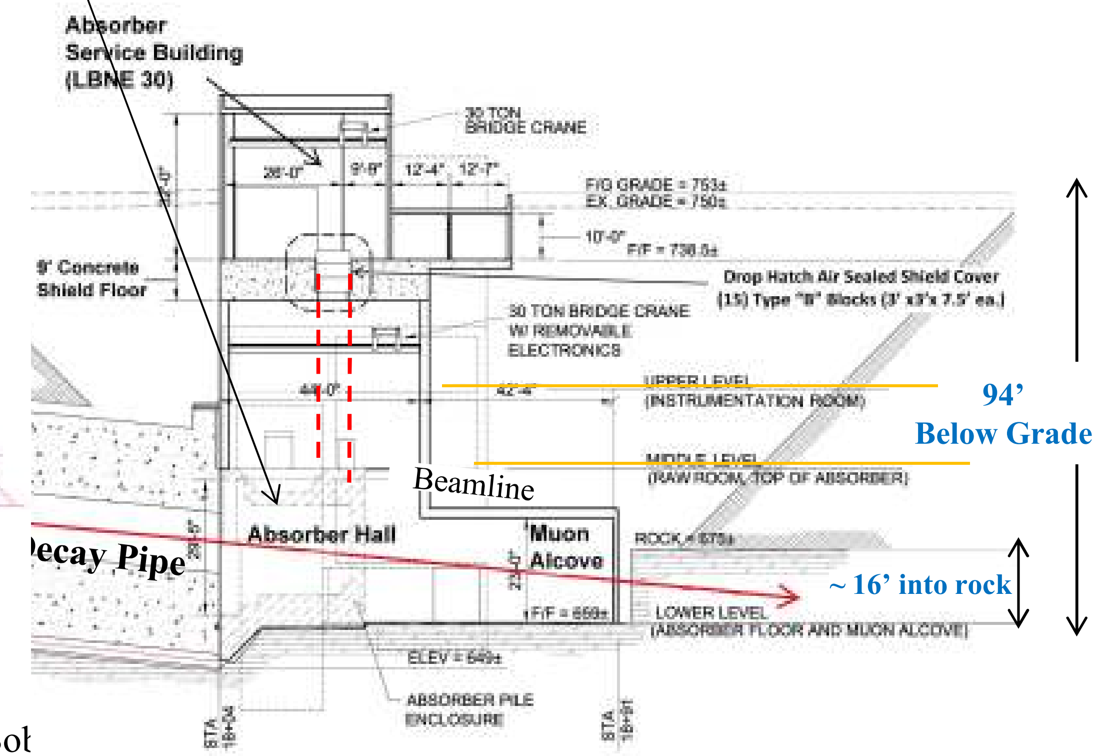
5.5 m of Concrete Shielding

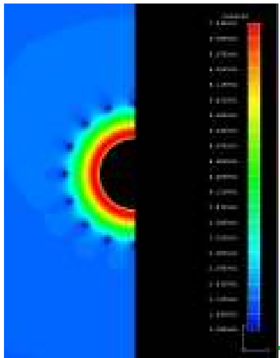
Absorber Complex – Longitudinal Section

The Absorber is conceptually designed for 2.3 MW

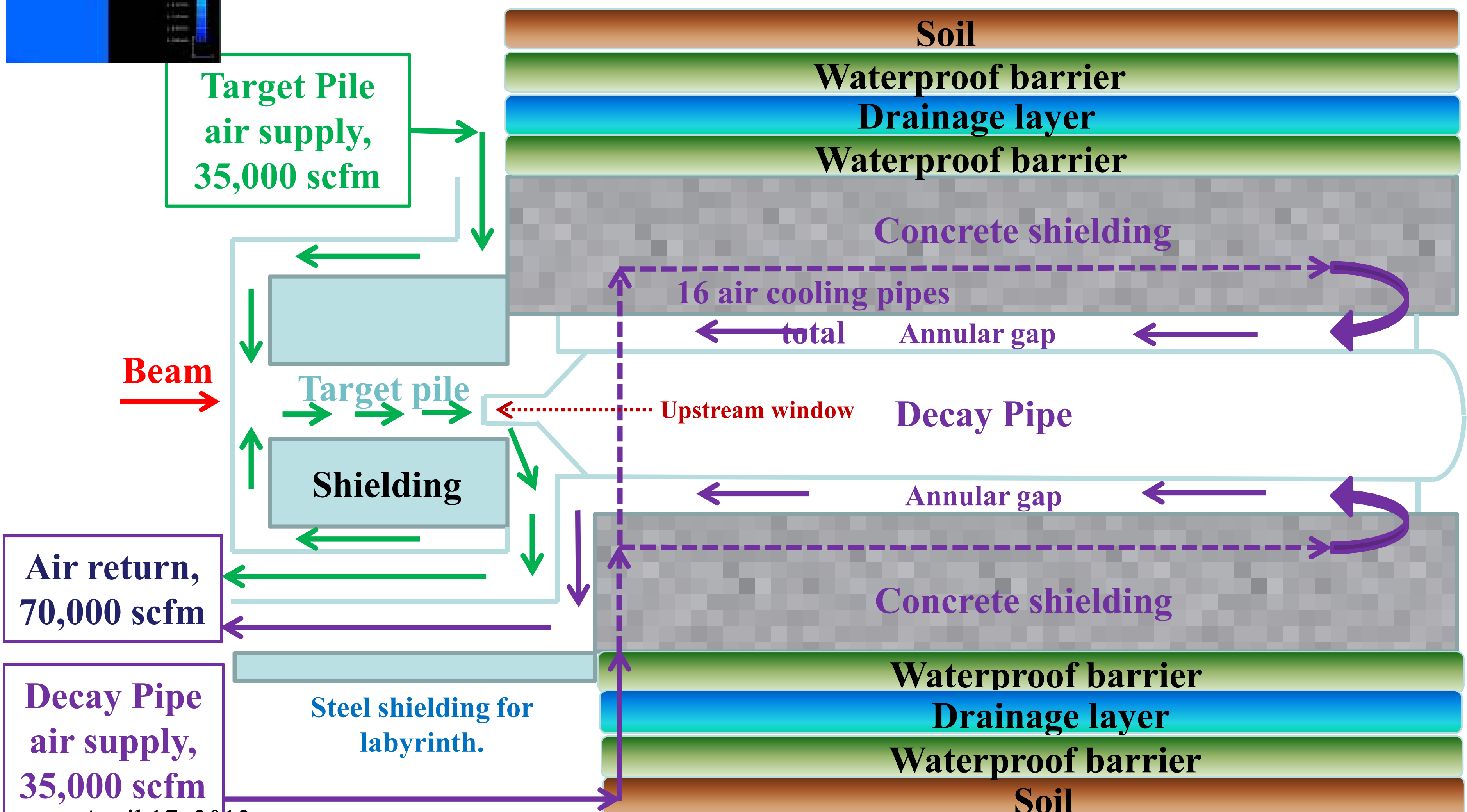
A specially designed pile of aluminum, steel and concrete blocks, some of them water cooled which must contain the energy of the particles that exit the Decay Pipe.



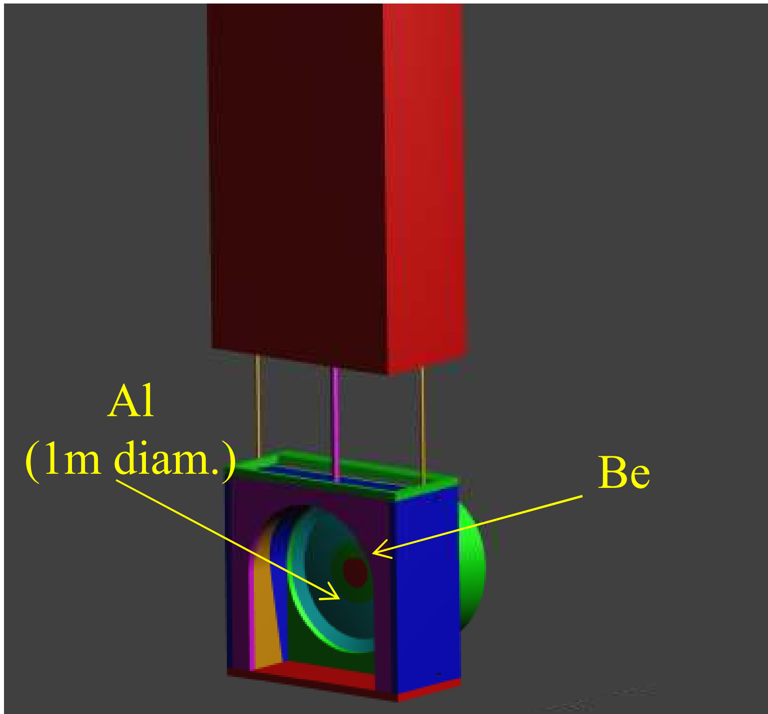




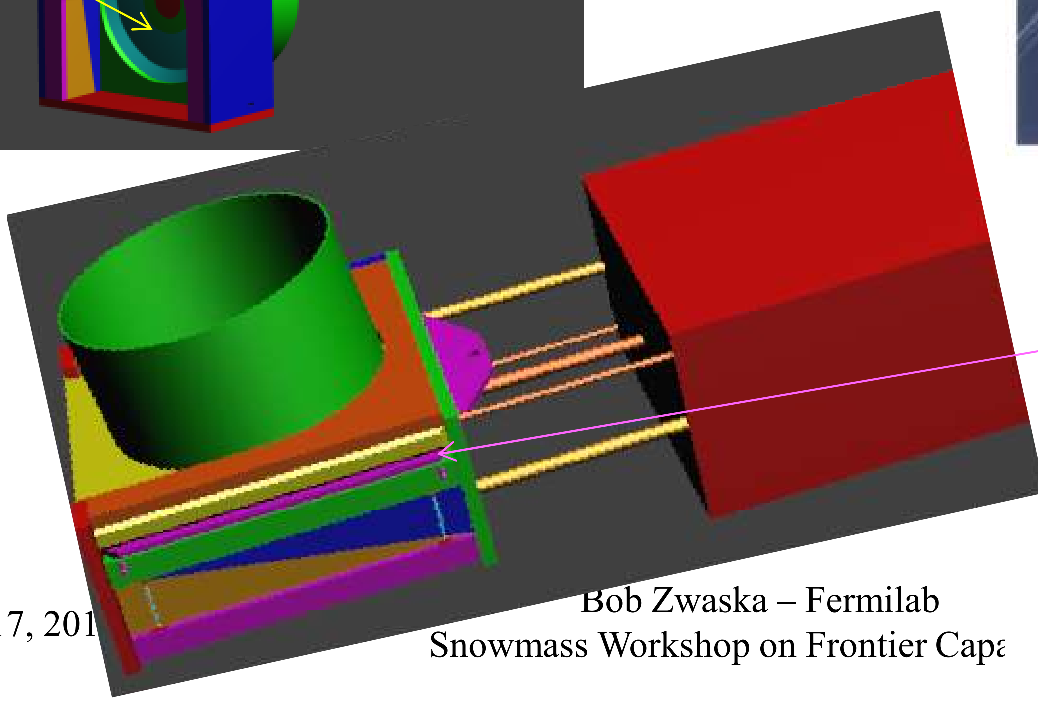
Helium-filled decay pipe, air-cooled.
Concentric decay pipe, both pipes are ½" thick.

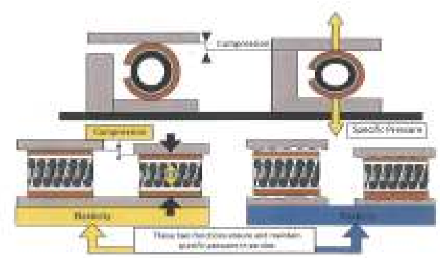


Current Concept for Replaceable Decay Pipe Window



- Screw Drive Actuator Will be Incorporated in Top Plate and Driven with Module-Thru Rods
- Water Cooling Plates not Shown
- Most Hardware Anodized Aluminum
- Utilizes Helicoflex Seal





Challenges to Conventional Neutrino Beams

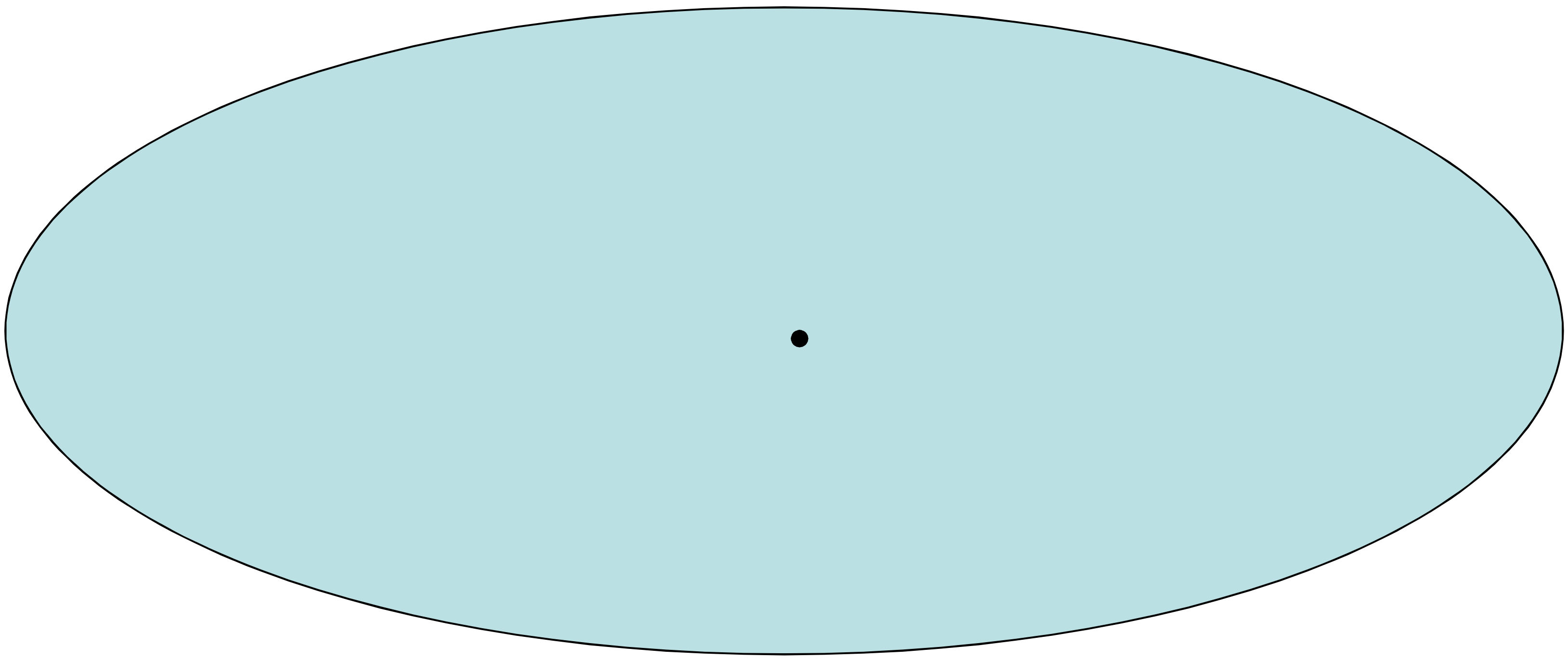
- Proton beams
- Targets
- Horns / focusing
- Precision
- Instrumentation
- Hadroproduction Modeling & Experiments
- Radiation Protection
- Radionuclide handling

Challenge: Proton Beam

- Increased beam power translates directly into neutrinos
- However, there are limitations on the beam delivered:
  - Spot size: small enough to optimize focusing, large enough to preserve target
  - Pulse length: short enough to allow short horn current pulses, long enough to preserve target
  - Stability: errant pulses can distort neutrino spectrum and destroy equipment
  - Losses must be kept very low in transfer lines, or more extensive shielding is required
- Single-turn extraction with tight beam optics is usually optimal
  - Larger emittances must be compensated by

Challenge: Proton Beam

- SNS & LBNE beams to scale:



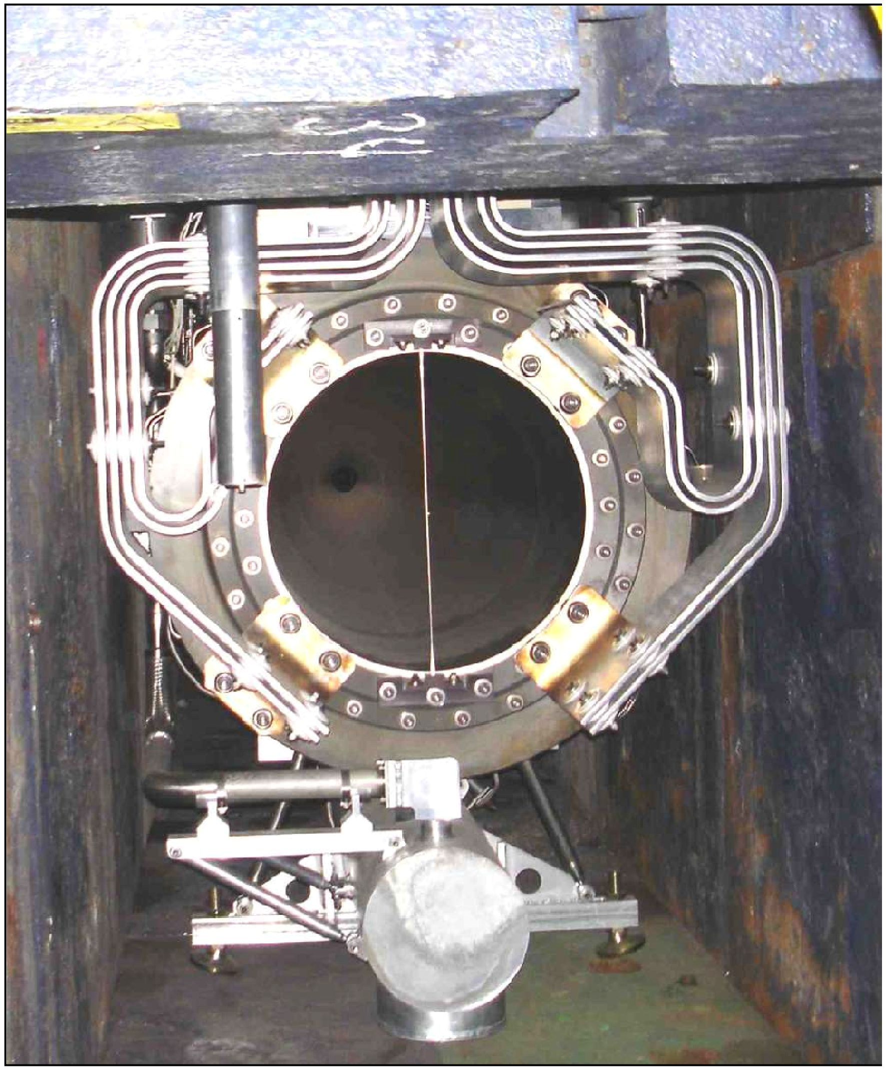
- 200 mm x 70 mm vs. 1.3 mm x 1.3 mm
  - ➢ SNS target experience is not directly transferrable

Challenge: Targets

- Optimal target:
  - Low-Z to optimize pion production (minimize energy deposition in target & horn)
  - High density to stay within the Horns' depth of focus
  - Roughly two nuclear interaction lengths long
  - The optimized width to allow a certain amount of reinteraction, but limit absorption
- But, the target must survive for a non-negligible duration
  - Material must withstand thermomechanical shock
  - Material must withstand radiation damage
  - Heat must be removed
  - Supporting materials (e.g. water & pipes) must be far enough from the beam to avoid boiling
- Above contradictions drive us to graphite & beryllium
  - Water cooling is the baseline, but air is not out of the question
  - **R&D** has a substantial capability to improve the efficiency of neutrino production

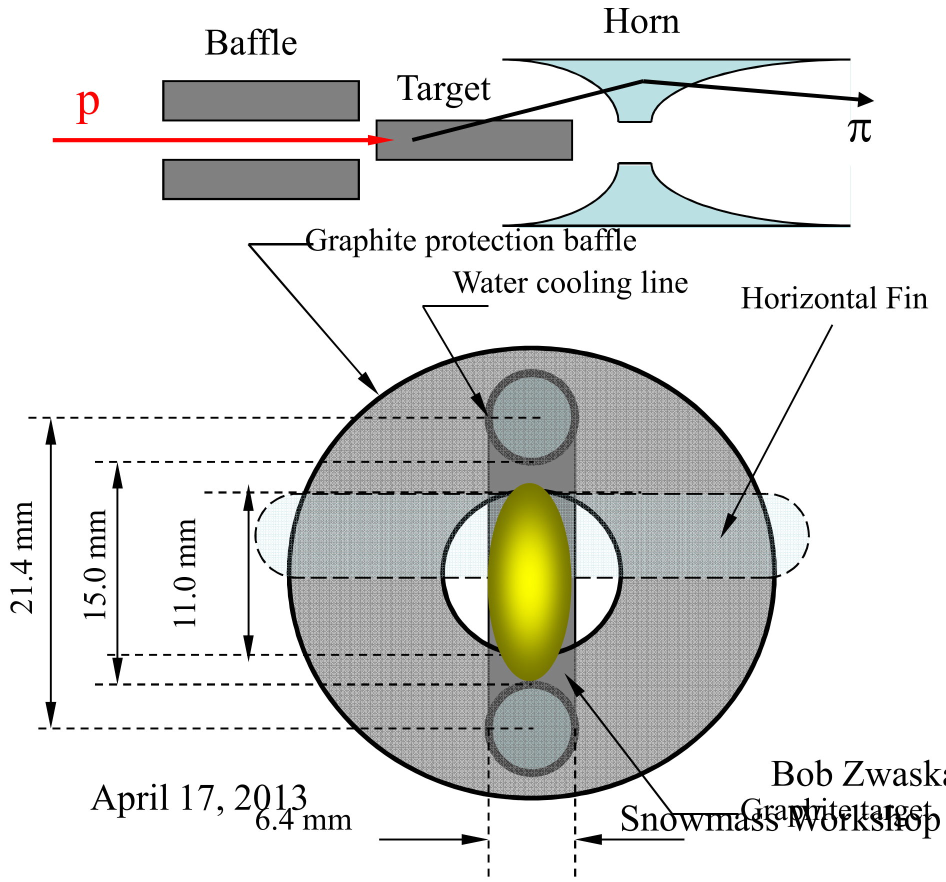
Challenge: Horn Focusing

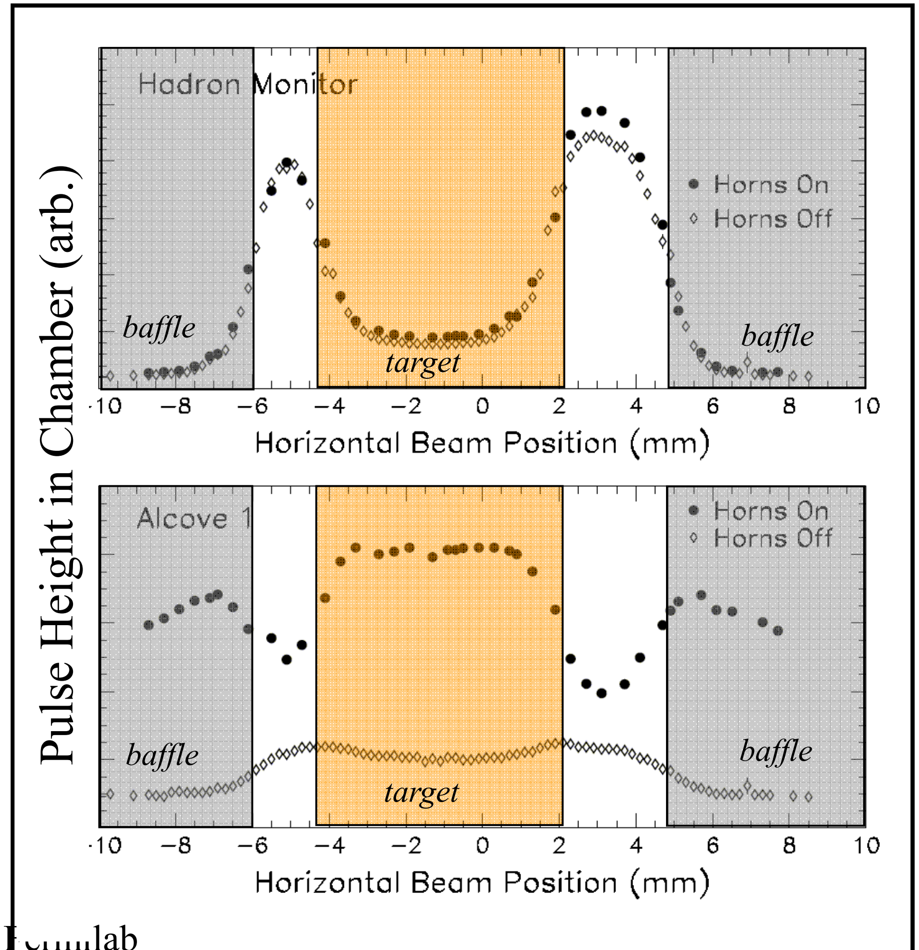
- Horns have a limited depth of focus
  - For a particular momentum in LBNE, roughly:
    - ± 5 mm transversely
    - ± 15 cm longitudinally
  - Target is much longer in *z* !
    - Not so bad: want a broad energy spectrum
  - Horn shapes and schemes can be optimized, even augmented by alternative focusing methods
- Horn currents are limited by ohmic and beam heating (~ 200 kA)
  - Higher currents would allow more efficient focusing
- Horn materials cause absorption and heating
  - Presently aluminum
  - **Beryllium is an R&D option**



Challenge: Precision NuMI Target Alignment

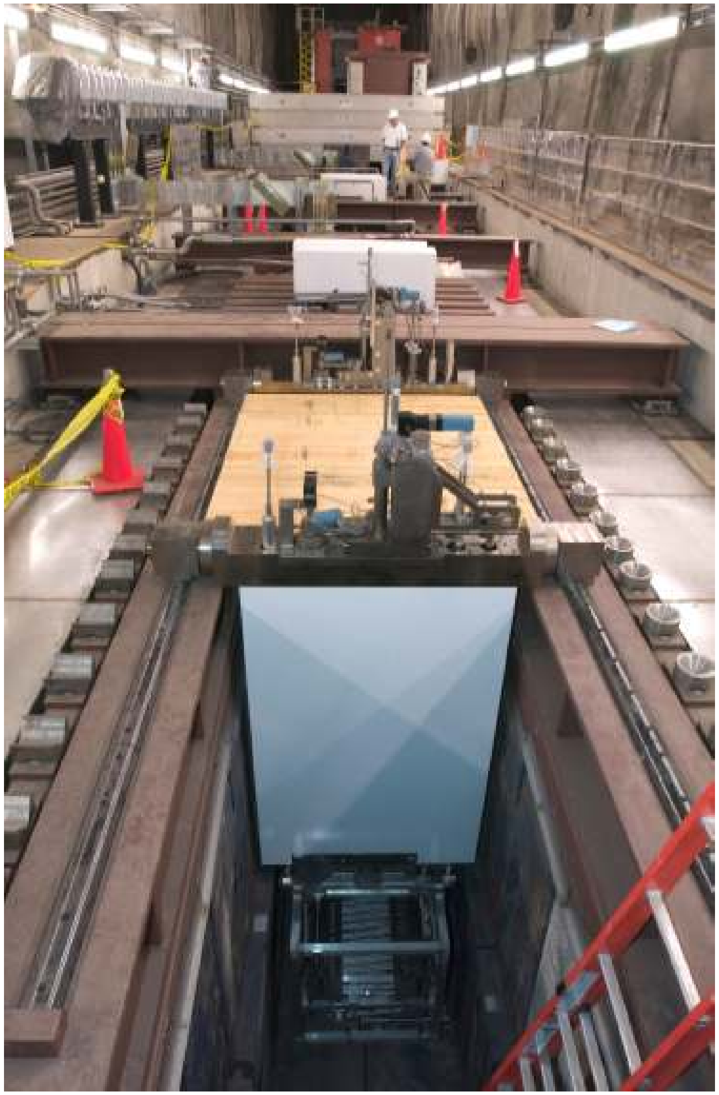
- Proton beam scanned horizontally across target and protection baffle
- Hadron Monitor used to find the edges
  - Measured small (~1.2 mm) offset of target relative to primary beam instrumentation.
  - Systematic effect of this misalignment would exceed statistical uncertainties





Why was the Target Misaligned?

- Aimed at the target by using correctors and 2 BPMs, 10 & 20 m upstream
  - BPM precision better than 0.1 mm
  - Everything aligned optically to few tenths of a mm
- Loading of the target hall
  - Shielding piled on top after the optical survey – this can be corrected
- Thermal deviation
  - Stations are fixed at different locations, move relative to eachother as temperatures change
  - Much more difficult to reduce



These Issues are Everywhere

- Gate at the top of my stairs installed in summer

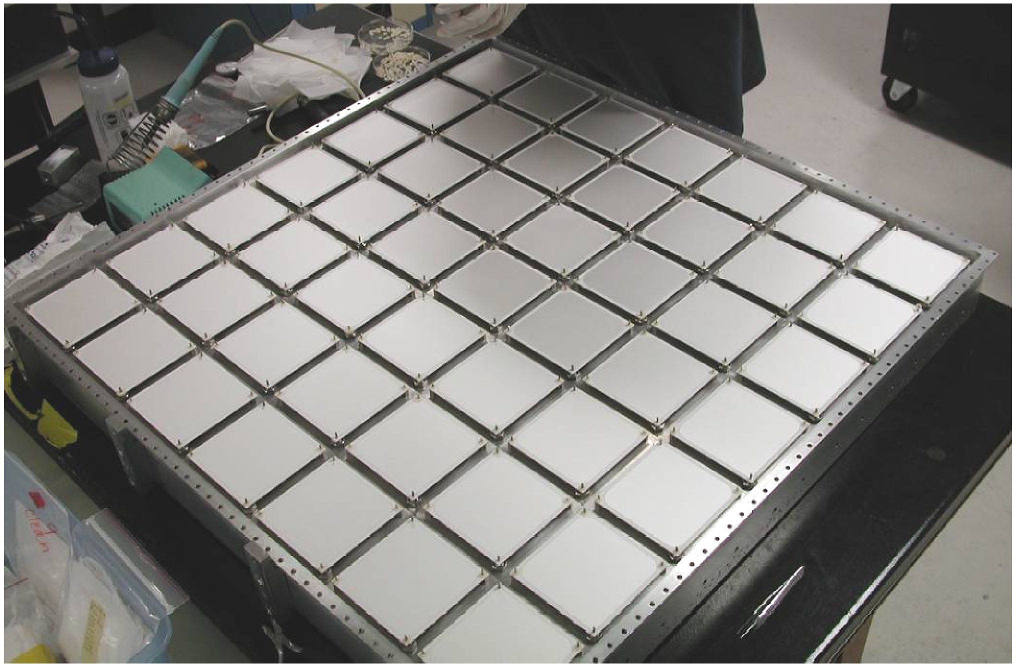
Tight Closure

Misaligned by ~ 2 mm

- Change of seasons in a temperature-controlled building caused a misalignment of 2 mm
- This difference accumulated over only 1 m of span
    - Here, it is a safety issue!
- We are fortunate we only had ~ 1 mm to deal with in NuMI

Challenge: Instrumentation

- Instrumentation can be used to measure beamline variations and to reduce the experimental limitations from them
- This instrumentation often needs to live within the secondary beam
  - Radiation-hard
  - Large signals
  - Cooling
- **R&D** on instrumentation would improve the precision of neutrino experiments



A Note on Near Detectors

- Differential Neutrino Event Spectrum:

$$n(E_R) = \int dE_T \phi(E_T) \sigma(E_T) \varepsilon(E_R; E_T)$$

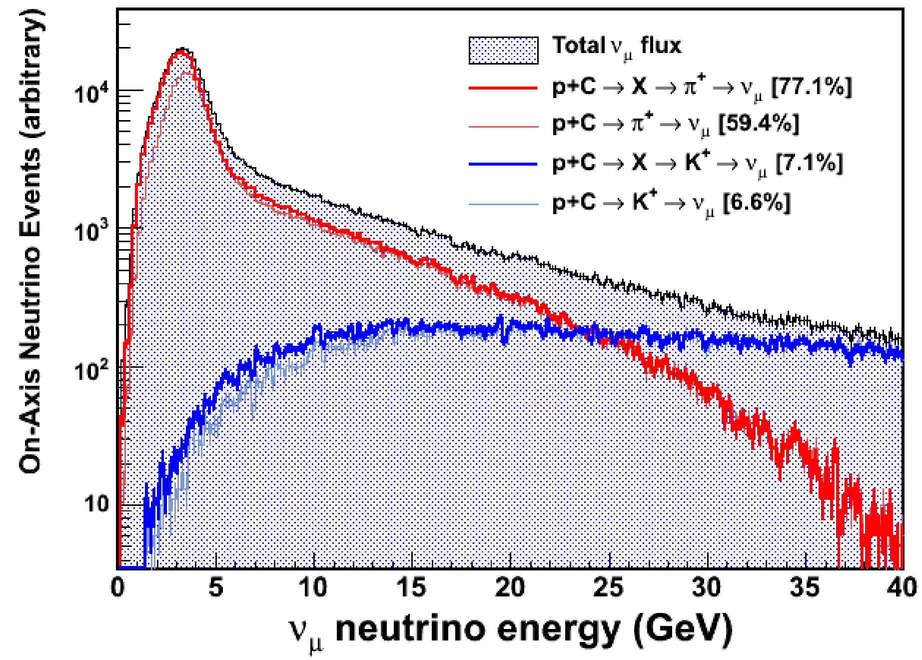
  - Depends on flux, cross section, and efficiency
    - Each has uncertainty
- A near detector reduces the uncertainty
  - Measures event spectrum at near location
    - Unfolding the cross sections and efficiencies gives the flux at near location
    - MC gives flux differences between detector locations
      - Less uncertain than absolute flux
    - Refold with far cross sections and efficiencies
  - Works best if detectors are the same
- For popular detector technologies (water, argon) the near detector must be substantially different than the far
- **Conclusion:** a near detector helps, but is not a panacea
  - Flux modeling crucial
  - Better cross section & efficiency knowledge helps

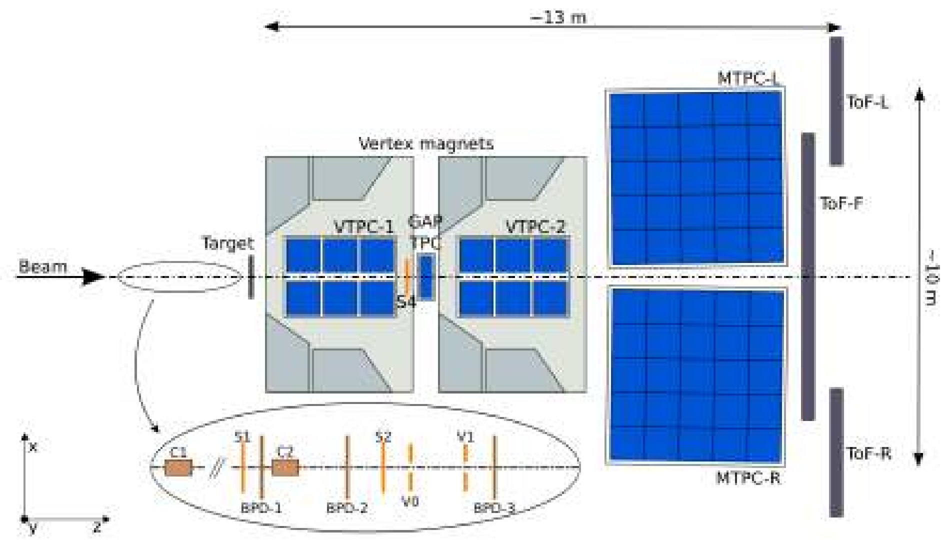
Challenge: Beam Modeling

- Modeling by hand from measured production cross sections falls well short in the required accuracy
- MC hadroproduction codes are used:
  - **GEANT:** gold standard, open code, but hadroproduction is tuned more for showers
  - **FLUKA:** best data agreement with neutrino experiments, but closed code – trust is not universal
  - **MARS:** well-used at Fermilab and good data agreement, but not a fully-available code and parts are closed
- GEANT is the most trusted code, but least accurate
- **Effort is needed** to tune codes and make them more useful
  - This does limit neutrino experiments

Challenge: Hadroproduction

- Simulations give a spectrum
  - ➢ But, what is the uncertainty?
- Hadroproduction experiments can constrain simulations, or directly give input to experiments' flux estimation
- Presently, NA-61 at CERN is exploring hadroproduction
  - ➢ Gradual series of measurements – not an exhaustive program
  - ➢ Some detector limitations mean that some important distinctions in parameter space can't be made
- **Solution:** a dedicated, exhaustive program of hadroproduction measurements could dramatically improve neutrino beam simulation





Challenge: Radiation/Radionuclide Management

- Shielding is not exciting
- But, it is a cost driver
- LBNE has an ocean of concrete, an expensive hydro-control system, and a closed air-cooling system
- Substantial cost-savings could be realized if more efficient shielding or management systems could be proven to be adequate
- Issues:
    - Penetration of radiation
    - Migration of radionuclides
    - Radiation-induced corrosion

Conclusion

- NuMI has been operating at up to 400 kW
  - Will operate at 700 kW for the rest of the decade
- LBNE a detailed designed
  - Accounts for many of the lessons learned from NuMI
  - Facility is designed for 2.3 MW, but replaceable components for 700 kW

- There are a number of opportunities whereby the state-of-the-art of conventional neutrino beams may be advanced
  - Targets, horns, precision, instrumentation, hadroproduction (modeling & experiments), shielding, etc.
  - R&D, effort, and experiments to address the above need to be part of the long-term plan

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Fermilab

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